Sub-ppm detection of vapors using piezoresistive microcantilever array sensors

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Abstract
The performance of microfabricated piezoresistive cantilever array sensors has been evaluated
using various vapors of volatile organic compounds including alkanes with different chain
length from 5 (*n*-pentane) to 14 (*n*-tetradecane). We demonstrate that piezoresistive
microcantilever array sensors have the selectivity of discriminating individual alkanes in a
homologous series as well as common volatile organic compounds according to principal
component analysis. We developed a new method to evaluate the sensitivity, taking advantage
of the low vapor pressures of alkanes with longer chains, such as *n*-dodecane, *n*-tridecane and
n-tetradecane, under saturated vapor conditions. This method reveals sub-ppm sensitivity and
the cantilever response is found to follow the mass of evaporated analytes as calculated using a
quantitative model based on the Langmuir evaporation model.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Microfabricated cantilever array sensors have attracted much
attention in recent years due to their real-time detection of
small amounts of molecules. Applications ranging from
chemistry to genomics have been demonstrated [1–7]. In
most of these studies, the bending or resonance frequency
change of a cantilever induced by the adsorption of analytes
on the cantilever has been detected using an optical (laser)
read-out system, which prevents the cantilever array sensors
from further miniaturization of the whole system. In addition,
the optical read-out system cannot be used for measuring
in opaque liquids, such as blood, because the optical signal
is attenuated due to low transmission or refractive index
change in such a solution. In contrast, piezoresistive
microcantilever array sensors do not require bulky and

expensive instrumentation [8, 9]. This approach contains
various advantages, such as low cost, simple operation,
and miniaturization of the whole system into a match-box
sized device. Moreover, cantilevers in two- or even three-
dimensional arrays can be integrated into the piezoresistive
read-out system [10–13].

Although a large number of studies on cantilever array
sensors has been reported so far, it is difficult to evaluate the
actual selectivity and sensitivity of these systems. Various
factors, such as analyte flow, temperature change, adsorption
of solvent vapors, and undesired physisorption of analytes
on the wall of the chamber or conduit tubes might lead to
incorrect sensitivity values. In this study, we evaluate the actual
performance of microfabricated piezoresistive cantilever array
sensors, utilizing vapors of various volatile organic compounds
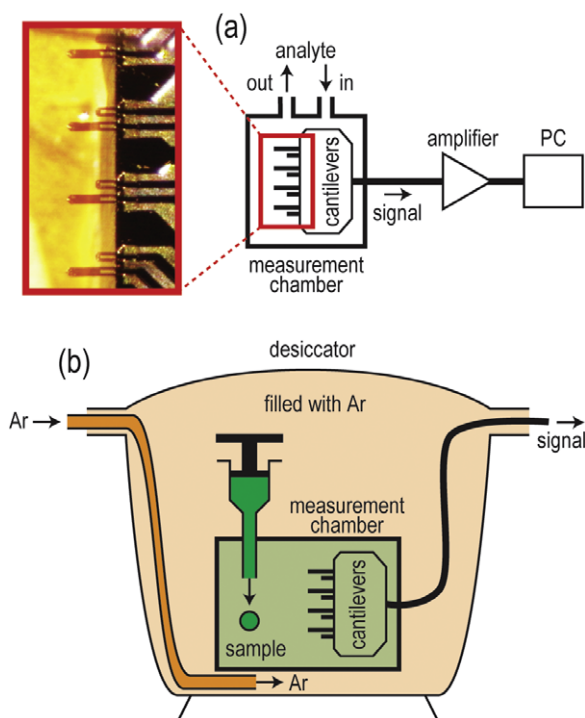including alkanes with different chain length. We demonstrate

Figure 1. Schematic illustrations of the setups of piezoresistive cantilever array sensors for (a) the selectivity evaluation measurements using various vapors and (b) the sensitivity measurements using alkanes with longer chain length under saturated vapor conditions (see text for details). A magnified image of a piezoresistive cantilever array is shown in the inset.

Figure 2. Response to each analyte of each cantilever coated with a different kind of polymer layer.

that piezoresistive cantilever array sensors have the selectivity of discriminating individual alkanes in a homologous series as well as other common volatile organic compounds. Each analyte is discriminated using principal component analysis of the pattern formed from the responses of polymer-coated cantilevers to the analytes. For the evaluation of sensitivity, we developed a new reliable method, which utilizes the low vapor pressures of the alkanes with longer chains under saturated vapor conditions. Using this method, we have succeeded in demonstrating reproducibly sub-ppm sensitivity, while the sensitivity of piezoresistive cantilever array sensors for volatile organic compounds has so far been reported to be several ppm [8, 9, 14–16]. The response of cantilevers is found to follow the mass of evaporated analytes as calculated using a quantitative model based on the Langmuir evaporation model [17].

2. Experimental details

The piezoresistive microcantilevers were fabricated in a similar procedure to that reported previously [10–12]. The fabricated cantilevers were 135 μm long, 30 μm wide and 1–1.5 μm thick, which led to low stiffness with typically measured spring constants of 0.1–0.5 N m^{-1} (inset of figure 1(a)). The deflection sensitivity is determined as $2 \times 10^{-7} \Delta R/R$ per Å. It should be noted that the shape and location of the piezoresistors have been optimized for force sensing as used for atomic force microscopy imaging. The piezoresistors were passivated with
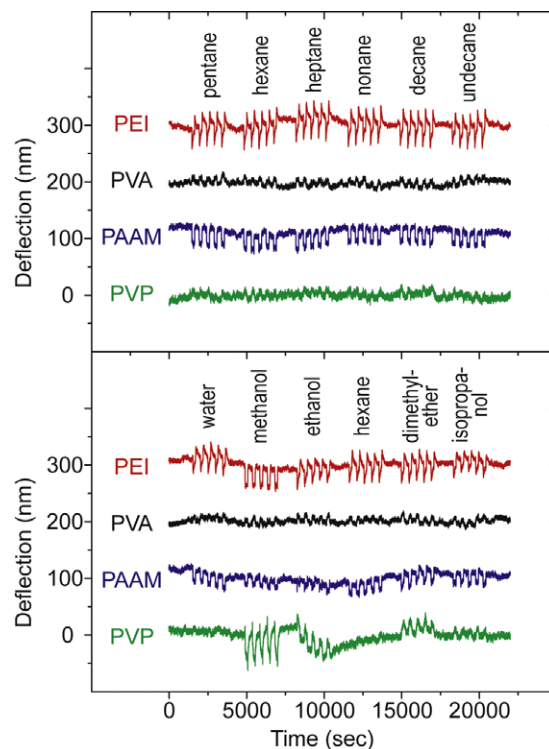
a 50 nm thick silicon nitride layer to decrease noise and to prevent degradation during measurements. Using an inkjet spotter, one side of each cantilever was coated with different polymers (poly-vinyl alcohol (PVA), poly-ethylene imine (PEI), poly-acryl amide (PAAM), and poly-vinyl pyrrolidone (PVP)), which serve as a receptor for gas molecules. The adsorption of analytes on the polymer layers induces surface stress due to swelling of the polymers, resulting in the bending of the cantilevers. For the compensation of thermal drift, the signal of each cantilever is corrected by subtraction of the response of an uncoated reference cantilever. Each set of a polymer-coated cantilever and an uncoated reference cantilever constitutes a Wheatstone bridge to detect the resistance change of the piezoresistor due to bending of the polymer-coated cantilever. The complete setups for the selectivity and sensitivity evaluation measurements are schematically shown in figure 1.

3. Results and discussions

3.1. Selectivity evaluations

We first evaluated the selectivity of the piezoresistive cantilever array sensors. Saturated vapor of the analyte gases mixed with the same volume of nitrogen gas in the mixing chamber were introduced into the measurement chamber for 3 min, followed by pure nitrogen gas flow for 5 min to purge the analytes from the polymer layer. This process was repeated five times for each analyte. Figure 2 shows the responses of the cantilevers coated with a different polymer layer to the various analyte

Table 1. Summary of the results of sensitivity measurements with a bandwidth of ∼3 Hz. P_{sat} and P_{part} are the saturated and partial vapor pressures of each alkane; S/N_{pk-pk} and S/N_{RMS} are signal to peak-to-peak noise and RMS noise ratios, respectively.
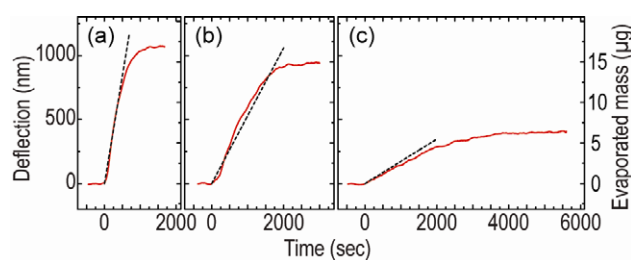
	P_{sat} (Pa)	P_{part} (ppm)	S/N_{pk-pk}	Sensitivity[a] (ppm)	S/N_{RMS}	Sensitivity[b] (ppm)
n-dodecane	9.90	97.7	130	0.75 ± 0.15	780	0.13 ± 0.03
n-tridecane	2.99	29.5	80	0.37 ± 0.10	480	0.061 ± 0.02
n-tetradecane	0.945	9.33	30	0.31 ± 0.10	180	0.052 ± 0.02

[a] The sensitivity based on S/N_{pk-pk}.

[b] The sensitivity based on S/N_{RMS}.
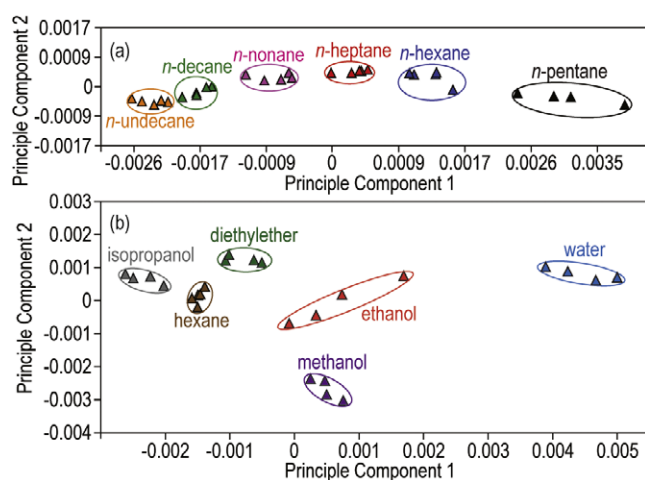
Figure 3. Principal component analysis case scores of (a) alkane molecules with different chain length and (b) various solvent vapors with different kinds of substituent.

Figure 4. Responses of the cantilever coated with PEI to alkane molecules with longer chain length, (a) *n*-dodecane, (b) *n*-tridecane and (c) *n*-tetradecane (solid red lines, left axis). Dotted black lines (right axis) correspond to the calculated total mass of evaporated molecules normalized with the result of *n*-dodecane.

vapors. Analyte-specific fingerprints were drawn by extracting four equidistant points in time from the data recorded during the purging process of each cycle. These fingerprints reflect the analyte desorption characteristics; they were found to result in a good separation of the analytes [2]. The fingerprints were analyzed using a commercial principal component analysis (PCA) software package (MVSP, multivariate statistical package, version 3.0, Kovach Computing Services, UK). PCA extracts the most dominant deviations in responses for various analytes. The largest differences in signal amplitudes of the fingerprint patterns are plotted using the two axes referring to projections of the multidimensional datasets into two dimensions (principal components). Each analyte yields well-separated clusters without any overlap, as shown in figure 3. The PCA case scores obtained demonstrate that piezoresistive cantilever array sensors have the selectivity of discriminating individual alkanes in a homologous series (figure 3(a)) as well as other common volatile organic compounds (figure 3(b)).

3.2. Sensitivity evaluations

To evaluate the sensitivity of piezoresistive cantilever array sensors, we took advantage of the low vapor pressures of alkanes with longer chains, *n*-dodecane, *n*-tridecane and *n*-tetradecane, under saturated vapor conditions. The measurement chamber was placed in a glass desiccator, purged with a constant flow of argon gas (100 ml min^{-1}) to avoid

undesired adsorption of volatile impurities. After sufficient purging of the whole chamber with argon (>30 min), a small amount (10 μl) of the alkane sample was injected into the measurement chamber and the measurement chamber was immediately closed. Evaporation of the alkane sample under saturated vapor conditions in the measurement chamber was monitored using a piezoresistive cantilever array, as shown in figure 4. The saturated vapor pressures of *n*-dodecane, *n*-tridecane and *n*-tetradecane molecules as well as the corresponding partial pressures are summarized in table 1. We determined the sensitivity by dividing the maximum signal (the value of deflection at the equilibrium state, e.g. 1050 nm, in the case of *n*-dodecane) by the noise level (8 nm, peak-to-peak noise; 1.3 nm root-mean-square (RMS) noise), which gives signal to noise ratios of 130 (peak-to-peak noise) and 780 (RMS noise). The sensitivity is determined by dividing the saturated vapor pressures of the alkanes by the signal to noise ratios. Accordingly, the sensitivity of the piezoresistive cantilever is determined to be 0.05–0.13 ppm (based on the signal to RMS noise ratio). The method applied here reveals much higher sensitivity of piezoresistive cantilever array sensors than that reported so far (1.2 ∼ several tens of ppm sensitivity to volatile organic compounds [8, 9, 14–16]). Since the limit of detection utilizing an optical read-out system has been determined as 0.2–20 ppm [2, 18, 19], the results obtained in the present study demonstrate that piezoresistive cantilever arrays have comparable or better sensitivity than optically read-out cantilever array sensors. Moreover, high frequency bridge measurements would enhance the sensitivity due to the reduction of $1/f$ noise, which decreases with increasing frequency [12]. It is worth noting that the sensitivity determined in this study is better than the detection

limit of other well-established mass sensitive gas sensors such as thickness shear mode resonators (TSMRs, quartz microbalances) or surface acoustic wave (SAW) devices [9].

3.3. The Langmuir evaporation model analysis

The responses of the cantilever to the alkanes were analyzed using the Langmuir evaporation model [17]. Here we assume that the injected liquid sample has a round shape, and the mass can be described as $m = 4\pi\rho a^3/3$, where ρ and a correspond to the density and radius of the spherical sample in the liquid state. According to the Langmuir model of the evaporation of small spheres, the rate of loss of mass can be expressed in the form

$$-\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{4\pi DMp}{RT}a, \qquad (1)$$

where D, M and p are the diffusion coefficient, the molecular weight and the vapor pressure of the evaporating substance, and R and T are the gas constant and absolute temperature, respectively. From these equations, the time dependence of the mass of the evaporated analyte m_e can be written as

$$m_e = m_0 - m = m_0 - \frac{4}{3}\pi\rho\left(a_0^2 - \frac{2DMp}{\rho RT}t\right)^{3/2}, \qquad (2)$$

where m_0 and a_0 are the initial mass and radius of the sample. Calculated values of m_e normalized with experimental data of *n*-dodecane are plotted in figure 4.[5] The response of the cantilever is fitted well with the total mass of evaporated analytes. The good agreement with the experimental results indicates that the bending of the cantilever is closely related to the mass of the evaporated analytes and that the cantilever can detect the evaporation of gas molecules from the beginning of evaporation. This quantitative model ensures that the bending of the cantilever is not caused by undesired impurities but by the analytes.

4. Conclusions

We have succeeded in demonstrating the high selectivity and sensitivity of piezoresistive cantilever array sensors. We demonstrate that piezoresistive cantilever array sensors have the selectivity of discriminating individual alkanes in a homologous series. The presented method to determine the sensitivity of a cantilever under saturated vapor conditions can provide reliable values without being affected by undesired effects mainly due to gas flow. This method reveals sub-ppm sensitivity of piezoresistive cantilever array sensors. The response of the cantilever is found to follow the mass of evaporated analytes using a quantitative model based on the Langmuir evaporation model. The experimental

evidence presented paves the way for further applications of piezoresistive cantilever array sensors offering various advantages, such as low cost, simple operation without time-consuming laser alignment, measurements in opaque liquids (blood) and miniaturization of the whole system into a matchbox sized device. Since ∼10 picomolar sensitivity has been achieved using optically read-out cantilever arrays in label-free detection of mRNA biomarker candidates in total cellular RNA [5], piezoresistive cantilever arrays having comparable or higher sensitivity are one of the most promising candidates for a mobile on-site diagnostic device as well as for genetic or environmental studies with high selectivity and sensitivity.

References

[1] Berger R, Delamarche E, Lang H P, Gerber C, Gimzewski J K, Meyer E and Güntherodt H-J 1997 Surface stress in the self-assembly of alkanethiols on gold *Science* **276** 2021–4
[2] Baller M K *et al* 2000 A cantilever array-based artificial nose *Ultramicroscopy* **82** 1–9
[3] Fritz J, Baller M K, Lang H P, Rothuizen H, Vettiger P, Meyer E, Güntherodt H-J, Gerber C and Gimzewski J K 2000 Translating biomolecular recognition into nanomechanics *Science* **288** 316–8
[4] Backmann N, Zahnd C, Huber F, Bietsch A, Pluckthun A, Lang H P, Güntherodt H-J, Hegner M and Gerber C 2005 A label-free immunosensor array using single-chain antibody fragments *Proc. Natl Acad. Sci. USA* **102** 14587–92
[5] Zhang J, Lang H P, Huber F, Bietsch A, Grange W, Certa U, McKendry R, Güntherodt H-J, Hegner M and Gerber C 2006 Rapid and label-free nanomechanical detection of biomarker transcripts in human RNA *Nat. Nanotechnol.* **1** 214–20
[6] Nugaeva N, Gfeller K Y, Backmann N, Duggelin M, Lang H P, Güntherodt H-J and Hegner M 2007 An antibody-sensitized microfabricated cantilever for the growth detection of Aspergillus niger spores *Microsci. Microanal.* **13** 13–7
[7] Watari M, Galbraith J, Lang H P, Sousa M, Hegner M, Gerber C, Horton M A and McKendry R A 2007 Investigating the molecular mechanisms of in-plane

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[5] The parameters used in figure 4 are as follows (given in the form parameter (unit), value for *n*-dodecane, value for *n*-tridecane, and value for *n*-tetradecane): ρ (g cm^{-3}), 0.752, 0.756, 0.767; D (cm^2 s^{-1}), 0.0229, 0.0220, 0.0212; M (g mol^{-1}), 170.33, 184.36, 198.39; p (Pa), 9.90, 2.99, 0.945. $a_0 = 0.134$ (cm), $R = 8.31$ (J mol^{-1} K^{-1}), and $T = 293$ (K). The diffusion coefficient D is determined using the classical hard sphere model: $1/3\lambda\overline{v}$, where λ is mean free path, estimated to be ∼36 nm assuming that the molecular diameter of alkanes is ∼0.5 nm, and $\overline{v}$ is the mean velocity equal to $\sqrt{8RT/\pi M}$.

mechanochemistry on cantilever arrays *J. Am. Chem. Soc.* **129** 601–9

[8] Jensenius H, Thaysen J, Rasmussen A A, Veje L H, Hansen O and Boisen A 2000 A microcantilever-based alcohol vapor sensor-application and response model *Appl. Phys. Lett.* **76** 2615–7

[9] Lange D, Hagleitner C, Hierlemann A, Brand O and Baltes H 2002 Complementary metal oxide semiconductor cantilever arrays on a single chip: mass-sensitive detection of volatile organic compounds *Anal. Chem.* **74** 3084–95

[10] Aeschimann L, Meister A, Akiyama T, Chui B W, Niedermann P, Heinzelmann H, De Rooij N F, Staufer U and Vettiger P 2006 Scanning probe arrays for life sciences and nanobiology applications *Microelectron. Eng.* **83** 1698–701

[11] Aeschimann L *et al* 2007 Piezoresistive scanning probe arrays for operation in liquids *J. Phys.: Conf. Ser.* **61** 6–10

[12] Polesel-Maris J *et al* 2007 Piezoresistive cantilever array for life sciences applications *J. Phys.: Conf. Ser.* **61** 955–9

[13] Lutwyche M *et al* 1999 5X5 2D AFM cantilever arrays a first step towards a terabit storage device *Sensors Actuators* A **73** 89–94

[14] Vancura C, Ruegg M, Li Y, Hagleitner C and Hierlemann A 2005 Magnetically actuated complementary metal oxide semiconductor resonant cantilever gas sensor systems *Anal. Chem.* **77** 2690–9

[15] Fadel L, Lochon F, Dufour I and Francais O 2004 Chemical sensing: millimeter size resonant microcantilever performance *J. Micromech. Microeng.* **14** S23–30

[16] Hierlemann A, Lange D, Hagleitner C, Kerness N, Koll A, Brand O and Baltes H 2000 Application-specific sensor systems based on CMOS chemical microsensors *Sensors Actuators* B **70** 2–11

[17] Langmuir I 1918 The evaporation of small spheres *Phys. Rev.* **12** 368–70

[18] Lochon F, Fadel L, Dufour I, Rebiere D and Pistre J 2006 Silicon made resonant microcantilever: dependence of the chemical sensing performances on the sensitive coating thickness *Mater. Sci. Eng.* C **26** 348–53

[19] Then D, Vidic A and Ziegler C 2006 A highly sensitive self-oscillating cantilever array for the quantitative and qualitative analysis of organic vapor mixtures *Sensors Actuators* B **117** 1–9